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A Structural Analysis on the Leaflet Motion Induced by the Blood Flow for Design of a Bileaflet Mechanical Heart Valve Prosthesis

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This paper presents a structural analysis on the rigid and deformed motion of the leaflet induced by the blood flow required in the design of a bileaflet mechanical heart valve (MHV) prosthesis. In the study on the design and the mechanical characteristics of a bileaflet mechanical heart valve, the fluid mechanics analysis on the blood flow passing through leaflets, the kinetodynamics analysis on the rigid body motion of the leaflet induced by the pulsatile blood flow, and the structural mechanics analysis on the deformed motion of the leaflet are required sequentially and simultaneously. Fluid forces computed in the previous hemodynamics analysis on the blood flow are used in the kinetodynamics analysis on the rigid body motion of the leaflet. Thereafter, the structural mechanics analysis on the deformed motion of the leaflet follows to predict the structural strength variation of the leaflet as the leaflet thickness changes. Analysis results show that structural deformations and stresses increase as the fluid pressure increases and the leaflet thickness decreases. Analysis results also show that the leaflet becomes structurally weaker and weaker as the leaflet thickness becomes smaller than 0.6 mm.

Key Words : Bileaflet Mechanical Heart Valve (MHV) Prosthesis, Structural Analysis, Blood Flow, Rigid Body Motion, Deformed Motion, Structural Deformations and Stresses, Leaflet Thickness, Structural Strength

1. Introduction

When the aortic valve in a human body is in malfunction, a mechanical heart valve (MHV) can be installed. Downstream of the MHV, elastic artery wall with sinus is located. In the blood flow passing through MHV and elastic artery, hemolysis and platelet activation causing thrombus formation can be seen owing to the shear stress in the blood. Also, fractures and deformations of leaflets can occur depending on the shape and material properties of the MHV. Therefore, a comprehensive study on the motion of leaflets associated with the blood flow in terms of fluid-solid interaction problem is needed in the study on the design and the mechanical characteristics of the MHV. Several studies (Yoganathan et al., 1978 ; Pantalos et al., 1990 ; King et al., 1996 ; Yang et al., 1994) have been reported on the blood flow passing through leaflet for single cycle with inelastic artery wall.

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In the present study, a structural analysis on the behavior of leaflet in conjunction with the blood flow is to be investigated to predict the structural strength of the leaflet. Here, the numerical analysis of deformations and stresses in the leaflet is to be carried out in association with reaction force at the hinge, leading to the establishment of design for a bileaflet MHV. Intrinsically, the design problem of a bileaflet mechanical heart valve is characterized by multidisciplinary interactions in which fluid mechanics, kinetodynamics, and structural mechanics are linked to each others. The interdependency of these discipline analysis modules in the current application contributes to difficulties in successfully implementing a holistic design synthesis strategy. Furthermore, such an integrated implementation is also subject to complexities introduced as a result of an increased number of design variables and constraints.

Structural optimization techniques, evolving integrating engineering design methodologies and computer aided engineering systems, have been applied to save the weight of structures in the fields of mechanical engineering, aeronautical engineering and civil engineering etc. using one numerical expression which defined the objective function, constraint function and design variables together with analysis softwares (Prager and Taylor, 1968 ; Vanderplaats, 1982 ; Rozvany et al., 1994 ; Kwon et. al., 2001). However, multidisciplinary analysis and design techniques, which may integrate design conditions conflicting with each other and manage simultaneously various engineering principles like structural mechanics, fluid dynamics, kinetodynamics, heat transfer and electromagnetics etc., are required to develop products which need engineering characteristics of multifunctions, high qualities, and high added values. MDO (multidisciplinary design optimization) methodology is an emerging technology to solve such a complicate structural analysis and design problem with a large number of design variables and constraints (Sobieszczanski-Sobieski, 1995 ; Alexandrov and Hussaini, 1997). In the classical structural design methodology which separates the complicate structural design problem and treats each separated unit problem, it is very hard to evaluate meanings of optimum design results, because most structural design variables are related to a large number of engineering phenomena. And also, all design variables sometimes converge to certain values before they reach optimum design values. Recent interest in the problems associated with multidisciplinary optimization is evidenced by an increased number of conferences, journals, and publications devoted to the subject. Numerous papers have been published recently which deal specifically with multidisciplinary optimization applications in such diverse areas as naval structural design, spacecraft design, automobile design, and aircraft design, etc.. The intuitive practice of breaking a large task into smaller, more manageable tasks was applied by Sobieszczanski-Sobieski (1995). Two review papers in the field of multidisciplinary synthesis are particularly noteworthy. Requirements and opportunities available in multidisciplinary analysis and synthesis applications are reviewed in Tolson (1985). Potentials and achievements of multidisciplinary optimization are reviewed in Sobieszczanski-Sobieski (1996).

Recently, MDO methodology using computer aided engineering systems is efficiently applied to solve a complicate large scale structural design problem (Sobieszczanski and Hafta, 1996 ;

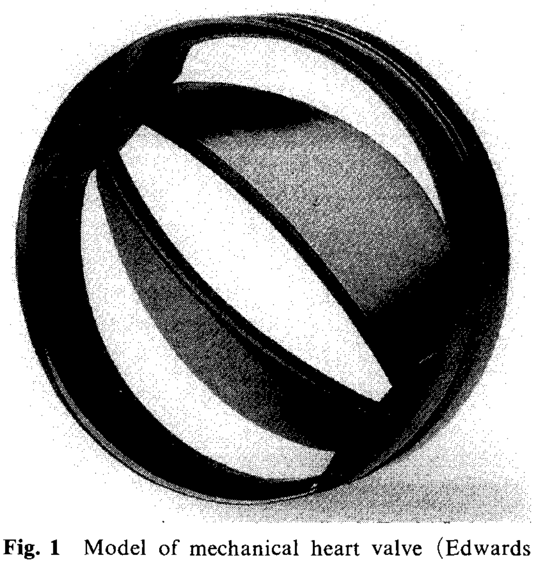

Fig. 1 Model of mechanical heart valve (Edwards MIRA Bileaflet MHV)

Stubbe, 1992 ; Tappeta et al., 1998 ; Giessing et al., 1995 ; Charmis, 1999 ; Rowell et al., 1999). Consequently, in the present study, computer aided engineering systems are adopted for the structural analysis on the leaflet motion induced by the blood flow for design of a bileaflet MHV. Computer aided engineering systems used for the present structural analysis study include ADAMS for the kinetodynamics analysis on the rigid body motion of leaflet, and NISA for the structural mechanics analysis on the deformed motion of leaflet. MHV model used in the present study is the Edwards MIRA bileaflet mechanical heart valve (see Fig. 1).

2. Kinetodynamics Analysis on the Rigid Body Motion of Leaflet

In this section, position, velocity and acceleration of the leaflet in rigid body motion with time are computed, and reaction forces and torques at joints are also computed to understand the dynamic characteristics of the mechanical heart valve. The kinetodynamics analysis of the mechanical heart valve is executed using ADAMS.

2.1 Blood flow and fluid forces applied on the leaflet of MHV

The fluid mechanics analysis of the blood flow passing through the bileaflet mechanical heart valve is required to calculate fluid forces applied on the leaflet surface. Fluid forces and moments computed in the study of the hemodynamics analysis of the blood flow (Choi et al., 2000) are employed for the current kinetodynamics analysis.

The diameter of the mechanical heart valve is 22.5 mm and the thickness of the leaflet is 0.65 mm. The Edwards MIRA mechanical heart valve features a curved leaflet profile as well as a slim, Carbofilm coated titanium-alloy housing. This combination is intended to optimize hemodynamic performance via a larger orifice, complementing natural flow pattern and minimizing turbulence. Desinged to reduce friction and wear, the valve's rolling hinge gives a constantly varying point of contact in the hinge area between the leaflet and the housing. An open channel in the hinge cavity allows continuous hinge washing during the entire cardiac cycle. The Edwards MIRA valve has unique sewing rings specifically designed for mitral and aortic applications, as well as a special aortic version for very small annuli. Each sewing ring design enhances the function of the valve in its position and size, including the unique hyperbolic shape of the mitral valve and the downstream extension of the aortic. Two semicircular leaflets open to 80° and the closing angle is 20°, resulting in a central, near laminar flow. Housing stability is increased by a stellite stiffener ring over a solid pyrolytic valve housing. The pivot hinge mechanism is located within the housing, and leaflet motion is by rotation and translation. Curved leaflets enhance central flow and rapid closure. The pivot ball and slot mechanism facilitate retrograde washing by relatively high velocity jets. Leaflets close on a circular ledge within the housing to reduce regurgitation and stress on the hinge mechanism. The pivot ball hinge closes by rotation and translation. Downstream of the mechanical heart valve, elastic artery wall with sinus is located. The artery wall is assumed to be an elastic circular tube with diameter of 25.0 mm. The blood flow is assumed to be a two dimensional incompressible pulsatile laminar flow.

The replaced mechanical heart valve is opened periodically by the pulsatile blood flow generated by the heart beat. The density of blood is assumed to be 1,000 kg/m^3, and the viscosity is assumed to be 4.0×10^{-3} kg/m·s. The pressure profile measured for each time through in vitro experiment is used as the boundary condition of the ventricle and the aorta. The number of heart beat is 75 beats/min. The blood velocity on the aortic valve wall is zero. The blood velocity on the surface of leaflets in motion is the same as the leaflet velocity.

The valve movement can be divided into four stages, i.e., the opening stage, the completely opened stage, the closing stage and the completely closed stage. In this research, three valve movement stages, i.e., the opening stage, the completely opened stage and the closing stage are studied.

As the heart ventricle shrinks, the leaflet starts to open to the maximum opening angle of 80° when the time reaches t=0.056 s. The maximum opening angle of 80° is maintained between t=0.0565 s and t=0.145 s. The closing stage of the leaflet starts at t=0.145 s. After t=0.2 s the valve closes rapidly. The leaflet movement of closing stage is faster as twice as that of opening stage. The normal force and the moment are all negative during opening and opened stages. After the time reaches t=0.144 s, the moment increases into positive value and the leaflet starts to close.

2.2 Kinetodynamics analysis model

The mechanical heart valve consists of three parts, i.e., the leaflet which controls the blood reverse flow, the orifice ring which supports leaflets and the sewing cuff which attaches and fixes the orifice ring to the tissue of the heart muscle. The kinetodynamics analysis of the leaflet of the mechanical heart valve is performed to get the reaction force at each joint. The kinematic model of the mechanical heart valve consists of three links and four joints. And the mobility of the leaflet movement is two. The solid model generated by ADAMS is shown in Fig. 2.

2.3 Analysis results and discussions

The absolute velocity of the leaflet tip is indicated in Fig. 3. The velocity and the acceleration of the leaflet is zero between t=0.056 s and t=0.145 s. And velocity and acceleration of the leaflet change rapidly after t=0.2 s when the valve starts to close rapidly. Fig. 4 indicates the reaction force at the joint during the valve movement. The reaction force changes very roughly while the leaflet keeps opening up to 80°. The reaction force at the joint increases rapidly after t=0.2 s when the leaflet starts to close. Hence, the structural deformation of the leaflet is expected at the closing stage of the valve movement when the maximum reaction force occurs at the joint. These constraint conditions may be used for the structural mechanics analysis of the mechanical heart valve in the next section.

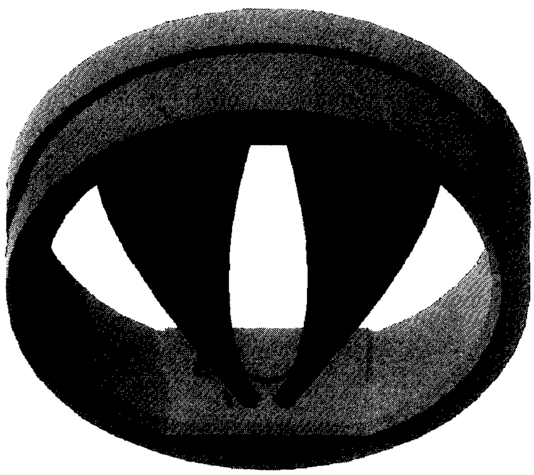

Fig. 2 Solid model of the Edwards MIRA bileaflet MHV (ADAMS, opening angle $\theta=60°$)

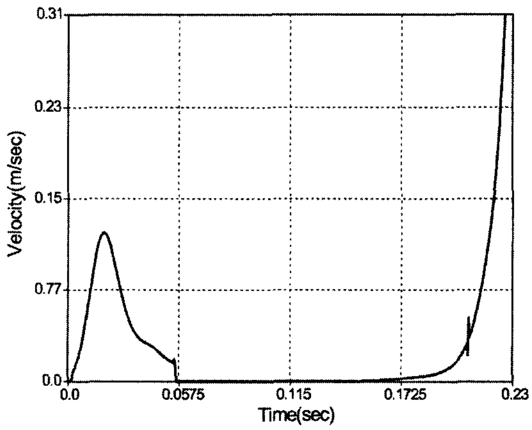

Fig. 3 Transient variation in the absolute value of the velocity of the leaflet tip

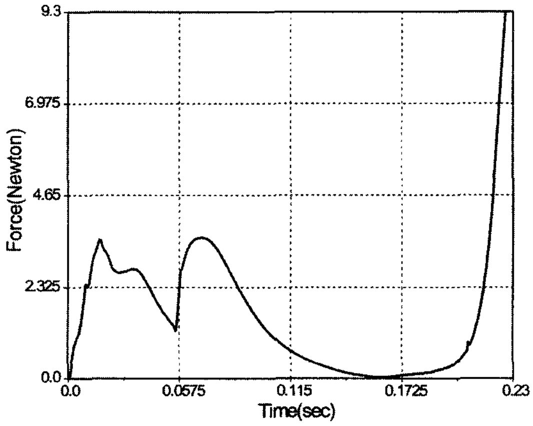

Fig. 4 Reaction force at the joint

3. Structural Mechanics Analysis on the Deformed Motion of Leaflet

Angular position of the leaflet and fluid forces applied on the leaflet at a time when the maximum structural deformation of the leaflet occurs should be known in order to execute the structural mechanics analysis of the leaflet. In this section, the interactive relations between the results of fluid mechanics analysis and of kinetodynamics analysis executed in the previous sections are considered as the substage of the structural analysis in the design of a bileaflet mechanical heart valve.

The angular position of the leaflet when the blood force applied on the leaflet becomes maximum was computed to be in the closing stage of the leaflet motion through the previous kinetodynamics analysis. Hence, the structural mechanics analysis on the deformed motion of leaflet is carried out at the closing angle of 20° to get structural strength variation as the leaflet thickness changes. NISA, a commercial finite element code, is used for the structural mechanics analysis.

Table 1 F.E. model data for the leaflet

Parameters		Data
No. of Nodes		15,489
No. of Element		13,136
Material Properties	E(Pa)	30.5E09
	ν	0.3
	ρ(Kg/m^3)	2,116

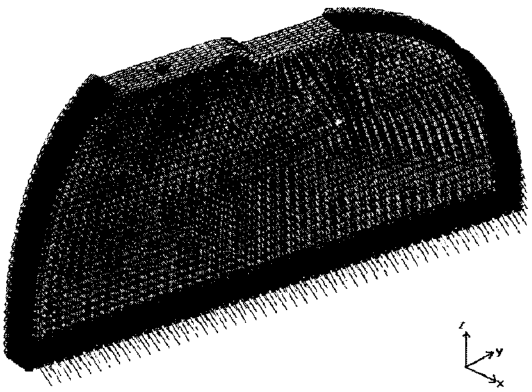

Fig. 5 F.E. model and constraint conditions for the structural mechanics analysis of leaflet (Edwards MIRA bileaflet MHV : thickness= 0.65 mm)

3.1 Analysis model and boundary conditions

The finite element model with constraint conditions for the structural mechanics analysis of the mechanical heart valve is shown in Fig. 5. The half of the leaflet is used as a model because of the geometric symmetry. The model consists of eight node hexahedron elements and eight elements are meshed in the direction of the leaflet thickness.

The orifice ring is neglected in the analysis, because it does not affect the analysis result. The orifice ring is assumed as a rigid body. Three degrees of freedom (u_x, u_y, u_z) are constrained at the hinge point and on the outer end surface of the leaflet which contacts the rigid orifice ring. The symmetric boundary condition ($u_y=0$) is applied on the symmetric surface ($y=0$), since both two leaflets contact each other on this symmetric surface and also the symmetric boundary condition ($u_z=0$) is applied on the symmetric surface ($z=0$) (see Fig. 5). The fluid force which is the external force applied on the leaflet is exerted as a normal uniform pressure onto the leaflet surface (see Fig. 5). The material of the leaflet is assumed to be Si-Alloyed PyC. Table 1 shows the finite element, node numbers and the material property values.

3.2 Analysis results and discussions

Structural deformation and stress distribution results obtained from the structural mechanics analysis are shown in Fig. 6 and Fig. 7. The maximum deformation occurs at the lower central part of the leaflet and the maximum stress at the hinge of the leaflet. And large stresses are also found at the lower part of the leaflet end surface. Fig. 8 indicates variations of the maximum deformation and Fig. 9 indicates variations of the maximum stress as the leaflet thickness increases from 0.5 mm to 0.75 mm.

As indicated in Fig. 9, the maximum stress occurring in the leaflet is smaller than the yield stress 407.7 MPa of the material for each leaflet

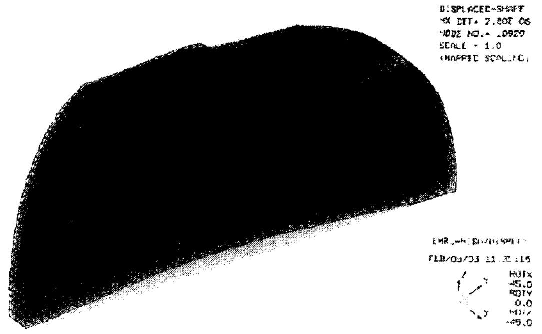

Fig. 6 Deformed shape of the leaflet (half model : thickness=0.65 mm)

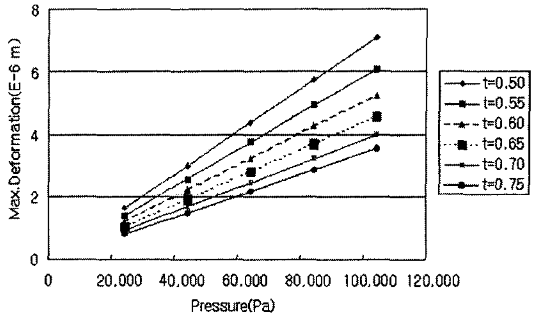

Fig. 9 Maximum deformation variation in the leaflet for various leaflet thicknesses and external fluid pressures (t=thickness, unit : mm)

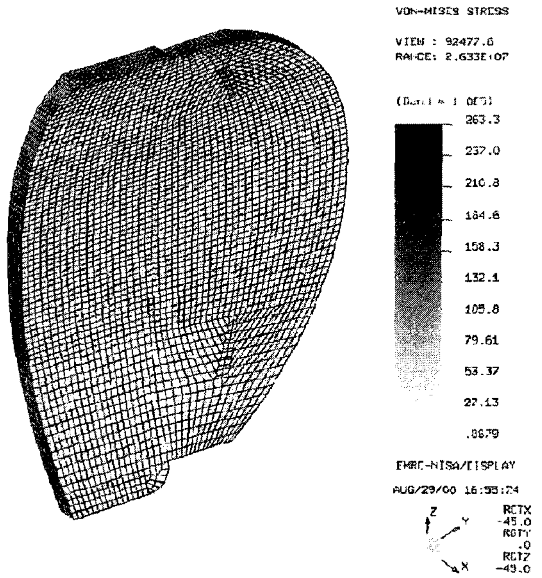

Fig. 7 Stress distribution in the leaflet (thickness= 0.65 mm)

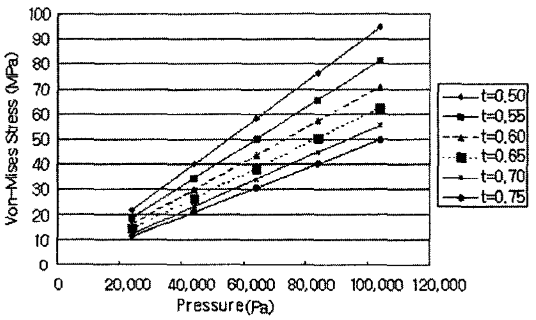

Fig. 10 Maximum von-Mises stress variation in the leaflet for various leaflet thicknesses and external fluid pressures (t=thickness, unit : mm)

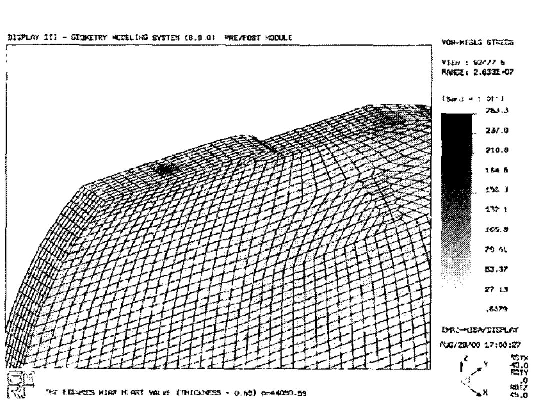

Fig. 8 Detailed stress stress distribution in the hinge part of the leaflet (thickness=0.65 mm)

thickness and external pressure. Hence, the leaflet is structurally strong enough in all cases, but the internal stress and deformation values increase as the leaflet thickness decreases. Therefore, the leaflet becomes structurally weak as the leaflet thickness decreases. As shown in Fig. 8, as the stress increases, the deformation also increases for all leaflet thicknesses. However, the slope of the straightline representing the deformation change with respect to pressure slightly increases as the thickness becomes smaller than 0.6 mm. Therefore, the structural strength of the leaflet decreases as the leaflet thickness decreases. Investigating all slope values of maximum deformation lines or maximum von-Mises stress lines for all suggested leaflet thicknesses, we may know that the slope values (about $0.6\sim0.7(\times10^{-10})$ for deformation line, $0.8\sim0.9(\times10^{3})$ for stress line) of deformation or stress lines for the leaflet thickness of

0.5 mm and 0.55 mm are about 1.5~2.0 times larger than the slope values (about 0.3~0.5($\times 10^{-10}$) for deformation line, 0.5~0.7($\times 10^{3}$) for stress line) of deformation or stress lines for the leaflet thickness of 0.6 mm, 0.65 mm, 0.7 mm, and 0.75 mm. This phenomenon means that much larger deformation or stress occurs inside the leaflet in cases of 0.5 mm and 0.55 mm leaflet thickness than cases of 0.6 mm, 0.65 mm, 0.7 mm and 0.75 mm leaflet thickness as the fluid pressure increases. Namely, the stress and deformation occurred inside the leaflets with 0.5 mm and 0.55 mm thickness increase about 1.5~2.0 times more largely than those occurred inside the leaflets with 0.6 mm, 0.65 mm, 0.7 mm and 0.75 mm thickness as the pressure increases. This phenomenon may suggest that the leaflet structure becomes weaker as the leaflet becomes thinner than 0.6 mm. This argument can be reasoned and justified from the viewpoint of the fact that since the leaflet opens and closes periodically and countlessly for the lifetime, even slight change in the strength of the leaflet structure may cause a damage to the MHV.

4. Conclusions

In this paper the structural analysis on the rigid and deformed motion of leaflet induced by the blood flow required in the design of a bileaflet mechanical heart valve is presented. The structural analysis requires the complicate several analyses in the field of fluid mechanics, kinetodynamics, and structural mechanics. Fluid pressure forces of the blood flow passing through the leaflet, computed in the previous hemodynamics analysis (Choi et al., 2000), are used as the external load constraint in the kinetodynamics analysis of the leaflet motion to get the reaction force at the hinge of the leaflet.

It is expected that the dynamic and structural characteristics of the leaflet of the Edwards MIRA mechanical heart valve won't change very much when parameters such as heart beat, artery diameter, etc. vary, even though the intensity (or the magnitude) of variables such as joint reaction force, the leaflet tip velocity, and the stress occurred in the leaflet may vary. Hence, further investigations in the case that parameters such as heart beat, artery diameter, etc. vary are not treated in this study.

The angular position of the leaflet when the reaction force at the hinge is maximum is identified through the kinetodynamics analysis of the leaflet motion. The closing angle of the leaflet is identified as the right one when the reaction force becomes maximum. Hence, the leaflet in the closing angle is used for the structural mechanics analysis to get the deformation and stress which occur in the leaflet on which the blood fluid force is applying. The structural mechanics analysis is performed as the leaflet thickness increases from 0.5 mm to 0.75 mm. The analysis result shows that the leaflet becomes structurally weaker and weaker as the leaflet thickness becomes smaller than 0.6 mm.

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